The formation of massive black holes in $z \sim 30$ dark matter haloes with large baryonic streaming velocities

Takamitsu L. Tanaka[1]⋆, Miao Li[2]

[1] *Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany*
[2] *Department of Astronomy, Columbia University, 550 W. 120th Street, New York, NY 10027, USA*

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ABSTRACT
The origins of the $\sim 10^9 \, \mathrm{M}_\odot$ quasar supermassive black holes (BHs) at redshifts $z > 6$ remain a theoretical puzzle. One possibility is that they grew from $\sim 10^5 \, \mathrm{M}_\odot$ BHs formed in the 'direct collapse' of pristine, atomic-cooling (temperatures $\gtrsim 8000 \, \mathrm{K}$; PAC) gas that did not fragment to form ordinary stars due to a lack of molecular hydrogen and metals. We propose that baryonic streaming—the relic relative motion of gas with respect to dark matter from cosmological recombination—provides a natural mechanism for establishing the conditions necessary for direct collapse. This effect delays the formation of the first stars by inhibiting the infall of gas into dark matter haloes; streaming velocities more than twice the root-mean-square value could forestall star formation until halo virial temperatures $\gtrsim 8000 \, \mathrm{K}$. The resulting PAC gas can proceed to form massive BHs by any of the mechanisms proposed in the literature to induce direct collapse in the absence of a ultraviolet background. This scenario produces haloes containing PAC gas at a characteristic redshift $z \sim 30$. It can explain the abundance of the most luminous quasars at $z \approx 6$, regardless of whether direct collapse occurs in nearly all or less than 1 per cent of PAC haloes.

Key words: black hole physics, cosmology: theory, cosmology: dark ages, reionization, first stars, galaxies: formation, quasars: supermassive black holes

1 INTRODUCTION

Observations of quasars at redshifts $z \approx 6-7$ reveal that supermassive black holes (SMBHs) with masses $M_{\mathrm{SMBH}} > 10^9 \, \mathrm{M}_\odot$ had already formed less than 1 Gyr after the Big Bang (Willott, McLure & Jarvis 2003; Fan 2006; Mortlock et al. 2011). The formation mechanism of these objects remains an open theoretical question (see reviews by Volonteri 2010 and Haiman 2013).

One hypothesis is that these objects grew from the remnants of the first (Population III or 'PopIII') stars (e.g. Madau & Rees 2001, Haiman & Loeb 2001, Shapiro 2005, Li et al. 2007, Pelupessy, Di Matteo & Ciardi 2007), which formed as gas collapsed through molecular hydrogen (H_2) cooling inside dark matter (DM) haloes with virial temperatures $T_{\mathrm{vir}} \sim 1000 \, \mathrm{K}$ at $z \sim 20-40$ (see the review by Bromm & Yoshida 2011). PopIII stars may have masses as large as $300 \, \mathrm{M}_\odot$ (Heger et al. 2003; Omukai & Palla 2001; Ohkubo et al. 2009) and as small as $\sim 10 \, \mathrm{M}_\odot$ (Turk, Abel & O'Shea 2009; Stacy, Greif & Bromm 2010; Clark et al. 2011; Greif et al. 2011a; Hosokawa et al. 2011),

leaving BHs with ~ 40 per cent of the stellar mass (Zhang, Woosley & Heger 2008).

The minimum time-averaged mass accretion rate for PopIII remnants to grow into the observed $z > 6$ SMBHs can be written as a fraction of the canonical Eddington limit, by comparing the number of required e-foldings gained via accretion to the amount of e-folding times available:

$$
\begin{aligned}
f_{\mathrm{Edd}} &\gtrsim \ln\left(\frac{M_{\mathrm{SMBH}}}{X_{\mathrm{merge}} \, M_{\mathrm{seed}}}\right) \Big/ \left[\frac{t_{\mathrm{avail}}}{(\eta/0.07) \, t_{\mathrm{Edd}}}\right] \\
&\approx \left[0.676 + 0.045 \ln\left(\frac{M_{\mathrm{SMBH}}}{3 \times 10^9 \, \mathrm{M}_\odot} \frac{30 \, \mathrm{M}_\odot}{M_{\mathrm{seed}}} \frac{30}{X_{\mathrm{merge}}}\right)\right] \\
&\quad \times \left(\frac{\eta}{0.07}\right)\left(\frac{t_{\mathrm{avail}}}{700 \, \mathrm{Myr}}\right)^{-1}.
\end{aligned}
\tag{1}
$$

Here, M_{seed} is the mass of the 'seed' BH; $X_{\mathrm{merge}} \sim 10-10^3$ (Tanaka & Haiman 2009; Tanaka, Perna & Haiman 2012) is the growth by BH mergers via hierarchical structure formation; $(\eta/0.07) \, t_{\mathrm{Edd}} = 31.5 \, \mathrm{Myr}$ is the e-folding timescale for a radiative efficiency $\eta \equiv L/(\dot{M}_{\mathrm{BH}} c^2)$ for luminosity L and accretion rate $\dot{M}_{\mathrm{BH}}$ scaled to the value derived by Merloni & Heinz (2008) and Shankar, Weinberg & Miralda-Escudé (2009) see also Shapiro (2005); and $t_{\mathrm{avail}} \approx 700 \, \mathrm{Myr}$ is the available time

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⋆ E-mail: taka@mpa-garching.mpg.de

from the formation of the earliest seeds at $z \gtrsim 40$ until $z \approx 7$. It is unclear whether such a large accretion rate can be sustained for such a long time. Interestingly, empirical measurements of the quasar duty cycle are indeed as high as $\gtrsim 0.5$ (Shankar, Weinberg & Miralda-Escudé 2009; Willott et al. 2010); the fact that the most massive haloes at these redshifts grow far more rapidly than in the local Universe (Angulo et al. 2012) could explain such prolific accretion activity. However, negative radiative feedback could reduce the accretion rate to a minuscule fraction of the required value, especially at early stages when the gravitational potential of the host halo is shallow (Alvarez, Wise & Abel 2009; Milosavljević et al. 2009).

An alternate path to SMBH formation is the 'direct collapse' of a gas cloud of nearly primordial composition and temperature $T \gtrsim 10^4 \, \mathrm{K}$ (Oh & Haiman 2002; Bromm & Loeb 2003; Koushiappas, Bullock & Dekel 2004; Lodato & Natarajan 2006; Spaans & Silk 2006; Dijkstra et al. 2008; Regan & Haehnelt 2009b,a; Shang, Bryan & Haiman 2010; Agarwal et al. 2012; Latif et al. 2013a). The paramount prerequisite for this scenario is that the fractions of H_2, metals and dust—strong coolants that trigger fragmentation into stars—be kept minimal. If this condition is satisfied, then compressional heating can balance cooling via atomic transitions. The cloud collapses nearly isothermally at $T \gtrsim 8000 \, \mathrm{K}$ to form a $\sim 10^5 \, \mathrm{M_\odot}$ star or star-like massive envelope (Begelman, Volonteri & Rees 2006; Hosokawa et al. 2013; Schleicher et al. 2013) that ultimately leaves behind a massive BH with a similar mass (Shibata & Shapiro 2002; Lodato & Natarajan 2007; Latif et al. 2013b).

To host such hot gas, the potential of the DM halo must be deep—i.e. its virial temperature must be $T_{\mathrm{vir}} \gtrsim 8000 \, \mathrm{K}$. However, as stated above, H_2 cooling usually triggers PopIII formation at a typical virial temperature value $T_{\mathrm{vir}} \sim 1000 \, \mathrm{K}$. The supernovae of these stars would distribute metals and dust, particularly if some PopIII stars are $\sim 100 \, \mathrm{M_\odot}$ (Greif et al. 2010); a single pair-instability supernovae may be sufficient to trigger the transition to Population II stars (Wise et al. 2012). Therefore, in order for direct collapse to occur, the host halo must experience minimal (massive) star formation from when $T_{\mathrm{vir}} \sim 1000 \, \mathrm{K}$ until $T_{\mathrm{vir}} \gtrsim 8000 \, \mathrm{K}$, a gap corresponding to a factor of $\gtrsim 20$ growth in halo mass.

A strong UV background, such as from nearby star-forming galaxies or quasars, could suppress the H_2 fraction through photodissociation, prevent PopIII formation as the halo accumulates mass, and lead to direct collapse once the halo reaches $T_{\mathrm{vir}} \sim 10^4 \, \mathrm{K}$ (Oh & Haiman 2002; Bromm & Loeb 2003; Dijkstra et al. 2008; Shang, Bryan & Haiman 2010). The time-averaged accretion rate required to grow into the most massive $z > 6$ SMBHs is lower for direct-collapse remnants than for PopIII seeds, but this is still a significant fraction of the Eddington limit:

$$f_{\mathrm{Edd}} \gtrsim \left[0.580 + 0.063 \ln \left(\frac{M_{\mathrm{SMBH}}}{3 \times 10^9 \, \mathrm{M_\odot}} \frac{10^5 \, \mathrm{M_\odot}}{M_{\mathrm{seed}}} \frac{3}{X_{\mathrm{merge}}} \right) \right]$$
$$\times \left(\frac{\eta}{0.07} \right) \left(\frac{t_{\mathrm{avail}}}{500 \, \mathrm{Myr}} \right)^{-1}. \quad (2)$$

Here, we have scaled the beginning redshift to 15 (approximately the earliest time at which stars or quasars can build

up a H_2-dissociating UV background; e.g. Agarwal et al. 2012) and reduced the factor X_{merge} to account for the rarity of massive BH seeds (Tanaka & Haiman 2009). Comparing equations 1 and 2, we see that while massive BH seeds formed from UV-aided direct collapse require a lower mean accretion rate than PopIII remnants, this rate still must be a significant fraction of Eddington for most of the age of the Universe at $z = 7$.

Haloes with $T_{\mathrm{vir}} \gtrsim 8000 \, \mathrm{K}$ can contain two different phases of gas (Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006; Dekel et al. 2009). Diffuse gas that is just below $8000 \, \mathrm{K}$ will be unable to cool efficiently, as atomic cooling is inefficient and such gas will have low H_2 densities (e.g. Oh & Haiman 2002). Gas that is denser will have a higher H_2 fraction and cool slightly faster, increase its H_2 fraction, etc. in a runaway fashion. Thus, atomic-cooling haloes can contain dense cold filaments embedded in diffuse, hot gas. The filaments can sink to the halo center at supersonic velocities, and may play a central role in SMBH growth at high redshifts by delivering large supplies of dense gas (Greif et al. 2008; Di Matteo et al. 2012). Supersonic turbulence may enhance the formation and velocities of cold filaments (Wise & Abel 2007; Greif et al. 2008; Wise, Turk & Abel 2008; Prieto, Jimenez & Haiman 2013).

Several studies have proposed ways in which direct collapse may occur in the absence of a UV background. *Collisional* dissociation can keep H_2 fractions low if the gas is hot ($T \gtrsim 8000 \, \mathrm{K}$) and dense ($n \gtrsim 10^3 \, \mathrm{K}$). Additionally, under such conditions the H_2 roto-vibrational levels saturate to local thermodynamic equilibrium, reducing the net cooling rate per molecule (Inayoshi & Omukai 2012). The gas could stay at a temperature of $\sim 8000 \, \mathrm{K}$ without forming H_2 if the neutral hydrogen column density is large enough to trap Lymanα cooling radiation (Spaans & Silk 2006; Schleicher, Spaans & Glover 2010; Latif, Zaroubi & Spaans 2011). Gravitational instabilities could transport angular momentum efficiently and lead to direct collapse (Begelman & Shlosman 2009). Gas can be more efficiently delivered to the deepest part of the potential if its angular momentum is low (Eisenstein & Loeb 1995; Koushiappas, Bullock & Dekel 2004; Lodato & Natarajan 2006). Recently, Inayoshi & Omukai (2012) proposed that direct collapse could be triggered by cold-accretion filaments shocking at the center of the halo. In each of these scenarios, the atomic-cooling, H_2-free cloud can collapse monolithically, much as in the UV background-aided picture of direct collapse. There are two significant theoretical uncertainties. First, prior PopIII formation and metal enrichment may facilitate cooling and fragmentation, preventing direct collapse. Again, the halo must grow by a factor $\gtrsim 20$ in mass without becoming significantly metal enriched. Second, these scenarios have not been thoroughly tested by detailed hydrodynamical simulations.

In this work, we propose that baryonic streaming motions (BSMs)—the velocity of baryons relative to DM at cosmological recombination (Tseliakhovich & Hirata 2010)—provide a natural mechanism for forestalling star formation and keeping the gas pristine until direct collapse can occur in any of the scenarios listed above. BSMs impede the infall of gas into early DM haloes, thus delaying PopIII formation until the velocities decay (as $\propto 1 + z$) and the haloes have deeper potentials (Stacy, Bromm & Loeb 2011; Greif et al.

2011b; Naoz, Yoshida & Gnedin 2013). For typical values of the streaming velocity—root-mean-square (rms) speed $\sigma_{\mathrm{BSM}}^{(\mathrm{rec})} \approx 30\,\mathrm{km\,s^{-1}}$ at recombination ($z \approx 1000$)—BSMs delay the formation of PopIII stars until the host halo mass has tripled (Greif et al. 2011b; see also Stacy, Bromm & Loeb 2011), compared to a theoretical situation where the velocity is zero. This delay has only a small impact on the globally averaged histories of reionization and SMBH formation[1] (Tanaka, Li & Haiman 2013)[2].

We will show that in very rare patches where the streaming velocities are more than twice the rms value, the most massive haloes at $z \sim 30$ could reach $T_{\mathrm{vir}} \gtrsim 8000\,\mathrm{K}$ before forming PopIII stars. Because gas falling into them would be pristine and have sufficiently large temperatures to be in the atomic-cooling regime, these exceptionally rare haloes would be natural sites where direct collapse could occur very early, without a UV background. We term these sites pristine atomic-cooling (PAC) haloes. We show that early formation of massive BHs via direct collapse in PAC haloes can explain the abundance of the most massive quasar BHs at $z \approx 6$–7, regardless of whether direct collapse occurs generically or very rarely (e.g. in less than one percent of cases) in $z \sim 30$ PAC haloes.

This paper is organized as follows. In §2, we present simple analytic arguments to show that at suitably high streaming velocity values, DM haloes can reach the atomic-cooling threshold before forming PopIII stars. We estimate in §3 the comoving number density of massive BHs formed in this way. We discuss several theoretical considerations and offer concluding remarks in §4.

Throughout this work, c, G, k_{B} and m_{p} denote the speed of light, the gravitational constant, the Boltzmann constant and the proton mass, respectively. Cosmological parameters for a Λ cold dark matter (ΛCDM) universe are denoted in the usual way: h, Ω_0, Ω_Λ, Ω_{b}, n_{s}, σ_8.

2 HALO MASS THRESHOLD FOR GAS INFALL AND POPIII FORMATION

In the absence of baryonic streaming, H_2 forms in gas accumulating inside haloes with $T_{\mathrm{vir}} \sim 400$–$1000\,\mathrm{K}$ (Haiman, Thoul & Loeb 1996; Tegmark et al. 1997); the gas then collapses to form stars. This threshold can be expressed

in terms of the halo circular velocity or halo mass:

$$v_{\mathrm{circ}} \equiv \sqrt{\frac{GM}{r_{\mathrm{vir}}}} = 3.7 \left(\frac{T_{\mathrm{vir}}}{1000\,\mathrm{K}}\right)^{1/2} \left(\frac{\mu}{1.2}\right)^{-1/2} \mathrm{km\,s^{-1}}; \quad (3)$$

$$M = 2.6 \times 10^5 \left(\frac{T_{\mathrm{vir}}}{1000\,\mathrm{K}}\right)^{3/2} \left(\frac{1+z}{26}\right)^{-3/2}$$
$$\times \left(\frac{h}{0.7}\right)^{-1} \left(\frac{\Omega_0}{0.27}\right)^{-1/2} \left(\frac{\mu}{1.2}\right)^{-3/2} \mathrm{M_\odot}, \quad (4)$$

where r_{vir} is the halo virial radius and μ is the mean molecular weight (e.g. Barkana & Loeb 2001).

BSMs delay gas infall, and increase the typical halo mass at which PopIII stars form. By analyzing the results of hydrodynamical simulation of PopIII formation that included this effect, Fialkov et al. (2012) fit the new circular velocity threshold v_{cool} to the following analytic form:

$$v_{\mathrm{cool}} = \sqrt{v_0^2 + [\alpha\,v_{\mathrm{BSM}}(z)]^2}. \quad (5)$$

They arrived at parameter values of $(v_0, \alpha) = (3.64\,\mathrm{km\,s^{-1}}, 3.18)$ and $(3.79\,\mathrm{km\,s^{-1}}, 4.71)$ for the results of Stacy, Bromm & Loeb (2011) and Greif et al. (2011b), respectively.

Naively, one might expect BSMs to negatively impact gas infall when $v_{\mathrm{BSM}} \sim v_{\mathrm{circ}} \approx 3.7\,\mathrm{km\,s^{-1}}$, i.e. that $\alpha \sim 1$. Instead, the simulations show that $\alpha \sim 4$, i.e. that streaming velocities that are only a fraction of the circular velocity is sufficient to delay PopIII formation. Plausibly, this is because the relevant velocity value is not the halo's circular velocity when stars finally form, but rather the value related to the infall of the gas at earlier times (when streaming motions are larger and the halo potential is shallower) and at a radius larger than the virial radius. Stacy, Bromm & Loeb (2011) suggested that the relevant velocity is the sound speed of the gas in the intergalactic medium when the gas first begins to fall into the halo potential, i.e. that BSMs raise the Jeans mass scale. Naoz, Yoshida & Gnedin (2013) showed that the filtering mass scale (Gnedin 2000; Naoz & Barkana 2007), which takes into account the thermal history of the gas, can more accurately explain the characteristic mass scale.

Additionally, the enhancement of two heating mechanisms could contribute to the delay in PopIII formation. Yoshida et al. (2006) found in their simulations that haloes with large mass accretion rates did not form PopIII stars right away, due to greater dynamical heating by the accreting matter. This heating rate is

$$(\gamma - 1)\frac{\mathrm{d}e}{\mathrm{d}t} \sim \frac{\mathrm{d}k_{\mathrm{B}}T_{\mathrm{vir}}}{\mathrm{d}t} \approx \frac{\mu m_{\mathrm{p}}G}{3r_{\mathrm{vir}}}\dot{M}_{\mathrm{halo}} \quad (\mathrm{dyn.\ heating}) \quad (6)$$

where γ is the adiabatic index and $e \equiv (\gamma-1)^{-1}k_{\mathrm{B}}T/(\mu m_{\mathrm{p}})$ is the internal energy of the gas per unit baryonic mass. Because on average the halo mass accretion rate is roughly proportional to the halo mass (Wechsler et al. 2002; Fakhouri, Ma & Boylan-Kolchin 2010, e.g.)[3], dynamical heating would be, on average, stronger in haloes where BSM delays gas accumulation. Similarly, the compressional heating rate of a collapsing gas cloud scales

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[1] BSMs may leave detectable imprints in the power spectra of galaxies, quasars and the 21 cm signature (Dalal, Pen & Seljak 2010; Maio, Koopmans & Ciardi 2011; Tseliakhovich, Barkana & Hirata 2011; McQuinn & O'Leary 2012; Visbal et al. 2012).

[2] Note that whereas Tanaka, Li & Haiman (2013) discussed the (weak) negative effect of BSMs on the formation of SMBHs from PopIII seeds, this paper discusses how BSMs could play a positive role by enabling the early formation of direct-collapse BHs.

[3] Equation 1 in Fakhouri, Ma & Boylan-Kolchin (2010) suggests $\dot{M}_{\mathrm{halo}} \sim 0.2M_{\mathrm{halo}}\,\mathrm{d}z/\mathrm{d}t$ within a factor of two for $10^5\,\mathrm{M_\odot} < M < 10^9\,\mathrm{M_\odot}$ and $\Omega_0(1+z)^3 \gg \Omega_\Lambda$.

with the free-fall timescale $t_{\rm ff} = \sqrt{3\pi/(32G\bar{\rho})}$ (e.g. Omukai, Schneider & Haiman 2008):

$$\frac{de}{dt} = p\frac{d\ln\rho_{\rm gas}}{dt} \sim \frac{k_BT}{\mu m_p}\frac{1}{t_{\rm ff}} \propto \bar{\rho}^{-1/2} \quad \text{(comp. heating)} \quad (7)$$

where p is the gas pressure and $\bar{\rho}$ is the combined mean density of gas and DM. In haloes where gas infall is delayed, the DM-to-gas ratio is initially greater than in haloes where this ratio is comparable to the cosmological average, and thus the compressional heating rate is higher (the free-fall time is shorter) at similar gas densities.

In what follows, we adopt the fitting formula of Fialkov et al. (2012; equation 5), accepting that it may be inaccurate by a factor of order unity compared to more explicit formulations of the characteristic mass for gas infall (Naoz, Yoshida & Gnedin 2013). We take $v_0 = 3.7\,{\rm km\,s^{-1}}$ and treat α as a free parameter of order ~ 4 as found by Fialkov et al. (2012). (Note that in the high-$v_{\rm BSM}$ regime of interest, the halo mass threshold is much more sensitive to α than to v_0.) The halo mass at which PopIII stars can form is

$$M_{\rm cool} \approx 3.5 \times 10^5 \left[1 + \left(\frac{2}{3}\frac{\alpha}{4}\frac{v_{\rm BSM}^{\rm (rec)}}{30\,{\rm km\,s^{-1}}}\frac{1+z}{21}\right)^2\right]^{3/2}$$
$$\times \left(\frac{1+z}{21}\right)^{-3/2} {\rm M_\odot}. \quad (8)$$

At adequately large velocities, gas infall and PopIII formation are delayed until the halo potential is deep enough to host atomic-cooling gas, i.e. $M_{\rm infall} > M(T_{\rm vir} = 8000\,{\rm K}) \approx 5.8 \times 10^6\,{\rm M_\odot}[(1+z)/26]^{-3/2}$ (see equation 4) [4]. Indeed, in their N-body simulations Naoz, Yoshida & Gnedin (2013) find that for $v_{\rm BSM}$ values more than ~ 2 times the rms value, the baryonic content of haloes in this mass range at $z \gtrsim 20$ is lower by a factor of several compared to the case $v_{\rm BSM} = 0$.

In the redshift range of interest, we expect the effect of a UV background to be negligible. Even for optimistic assumptions for the required local Lyman-Werner flux to induce direct collapse, Agarwal et al. (2012) found that direct collapse does not occur until $z \approx 16$. As we show below (Figure 3), the PAC halo formation rate peaks at $z \approx 30$, and falls by several orders of magnitude by $z \approx 16$. Moreover, our PAC haloes form preferentially in regions of space where prior star formation is suppressed due to the local streaming velocity being faster than the cosmic average; thus, these sites should anti-correlate with peaks in the UV flux.

In Fig. 1, we present the halo mass threshold for PopIII formation as a function of redshift, by evaluating equations (5) and (8) for streaming velocity magnitudes of $v_{\rm BSM}^{\rm (rec)} = 30\,{\rm km\,s^{-1}}$ (the rms value), $60\,{\rm km\,s^{-1}}$, $75\,{\rm km\,s^{-1}}$ and $90\,{\rm km\,s^{-1}}$. The figure can be read as follows. The solid curves in each panel show the halo masses corresponding to virial temperatures of $1000\,{\rm K}$ and $8000\,{\rm K}$, as labeled in panel (a). The dotted red, short-dashed green and long-dashed blue curves show the mass threshold for gas to collapse inside haloes, for assumed values of $\alpha = 3.2$, 4.0 and 4.7, respectively; these values were chosen to span the range in α found

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[4] The mass threshold for atomic cooling may be larger by a factor of order unity (see e.g. Fernandez et al. 2013), e.g. if the relevant molecular weight of the gas is $\mu = 0.6$ (ionized) as opposed to $\mu = 1.2$ (neutral).
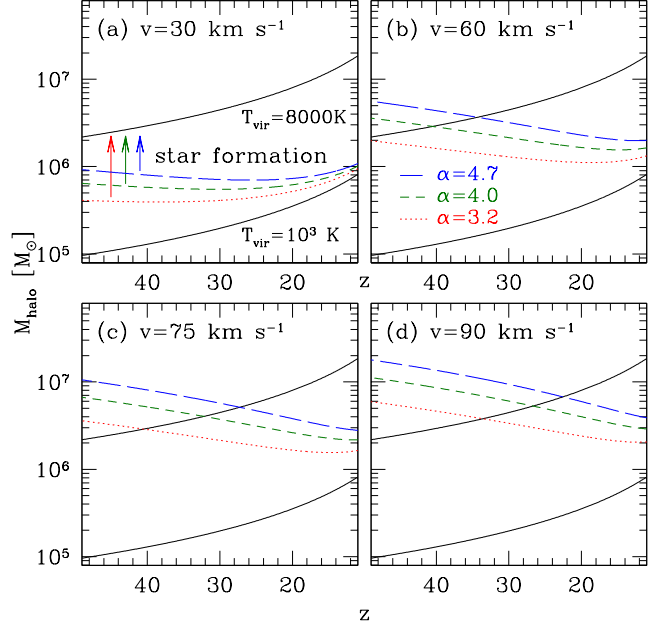
Figure 1. Characteristic halo mass scales. In each panel, the black curves show, as a function of z, the halo mass corresponding to $T_{\rm vir} = 8000\,{\rm K}$ (threshold for halo to host atomic-cooling gas) and to $T_{\rm vir} = 1000\,{\rm K}$ (threshold for PopIII formation in the absence of streaming velocities). The colored curves in each panel show the increase threshold for PopIII formation as estimated by Fialkov et al. (2012; equation 8) in the presence of various values of the streaming velocity at $z \approx 1000$: $30\,{\rm km\,s^{-1}}$ (the rms value), $60\,{\rm km\,s^{-1}}$, $75\,{\rm km\,s^{-1}}$ and $90\,{\rm km\,s^{-1}}$ in panels (a) through (d), in that order. The colored and styled lines denote different assumptions for the parameter α: 3.2 for red dotted curves, 4.0 for green short-dashed curves and 4.7 for blue long-dashed curves. For streaming velocities more than twice the rms value, the threshold for PopIII formation can exceed the one for atomic cooling. (A color version of this figure is available online.)

by Fialkov et al. (2012), with $\alpha = 4.7$ corresponding to the high-resolution moving-mesh simulations of Greif et al. (2011b) At any given z and $v_{\rm BSM}^{\rm (rec)}$, haloes with masses below the values indicated by the colored curves will have gas infall delayed by BSMs, and the gas inside them will not have collapsed to form PopIII stars. Haloes with masses above the curved curves will form compact baryonic objects; those with virial temperatures $T_{\rm vir} < 8000\,{\rm K}$ will undergo molecular cooling and form PopIII stars, whereas those with $T_{\rm vir} > 8000\,{\rm K}$ would form PAC clouds and possibly serve as the cradles of massive BHs.

3   COMOVING NUMBER DENSITY OF MASSIVE BHS FORMED VIA BARYONIC STREAMING

The potential direct-collapse sites proposed here are expected to be very rare, combining two unusual characteristics. First, they must be very precocious, with masses of $\sim 10^7\,{\rm M_\odot}$ at $z \gtrsim 20$, and be of order ~ 10 times more massive than the typical contemporary haloes forming PopIII stars. (Note that even streaming velocities close to the rms

value reduce by a factor of a few the gap in halo mass between PopIII formation and atomic cooling.) Second, these sites must lie in regions of space where the streaming velocities are $\gtrsim 2$ times the rms value. We now turn to estimating the comoving number densities of these sites.

3.1 Semi-analytic estimates

We quantify in Fig. 2 the rarity of several relevant types of objects. In panel (a), we plot the theoretical comoving number density of the most massive haloes at $z = 6$,

$$n_{\rm halo}(> M, z = 6) = \int_M^\infty \frac{dn}{dM'}(z = 6) \, dM'. \qquad (9)$$

The solid line shows the results for our adopted cosmological parameters—$h = 0.7$, $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_{\rm b} = 0.047$, $\sigma_8 = 0.83$ and $n_{\rm s} = 0.96$—while the dotted and dashed lines show the results for parameters according nine-year results of the *Wilkinson Microwave Anisotropy Probe* (*WMAP9*; Hinshaw et al. 2013) and the first data release of the *Planck* mission (Ade et al. 2013), respectively. The results for the three different sets of parameters effectively overlap, in this panel as in panels (b) and (d) discussed below, demonstrating that that our choice for the parameters are consistent with the latest empirical results. The thick black curves show the prediction for the Sheth-Tormen mass function for ellipsoidal collapse of DM haloes (Sheth & Tormen 2002), whereas the thin grey curves show that for the Press-Schechter mass function for spherical collapse (Press & Schechter 1974). The former is known to give better agreement with cosmological *N*-body simulations, especially at the massive end of the mass function (e.g. Reed et al. 2007). Panel (b) shows the comoving number density of atomic-cooling haloes as a function of z, i.e.

$$n_{\rm halo}(T_{\rm vir} > 8000\,{\rm K}, z) = \int_{M(8000\,{\rm K})}^\infty \frac{dn}{dM'} \, dM'. \qquad (10)$$

The line styles denote the assumed cosmological parameters and the mass function in the same way as in panel (a).

Panel (c) shows $p(> v)$, the probability that a random point in space has a recombination value of the streaming velocity above v. This is simply the cumulative distribution Maxwell-Boltzmann distribution function with an rms value of $30\,{\rm km\,s^{-1}}$. Finally, in panel (d) we present the comoving number density of PAC haloes, i.e. those haloes with $T_{\rm vir} > 8000\,{\rm K}$ and that have not yet formed stars due to their lying in a region in space with a large streaming velocity:

$$n_{\rm halo}({\rm PAC}) = \int_{M(8000\,{\rm K})}^\infty \frac{dn}{dM'} \, p(> v_{8000}) \, dM', \qquad (11)$$

where v_{8000} is the streaming velocity value at which $M_{\rm cool}$ exceeds the halo mass corresponding to $T_{\rm vir} = 8000\,{\rm K}$. As in Fig.1, the cases with $\alpha = 3.2$, 4.0 and 4.7 are shown in red, green and blue. For simplicity, we have only plotted cases for the Sheth-Tormen mass function.

Note that the comoving number densities presented in panels b) and d) of Fig. 2 do not account for the fact that BSMs suppress the number density of DM haloes at high redshifts (by a factor ~ 2 at $z \gtrsim 30$; Tseliakhovich & Hirata 2010; Naoz, Yoshida & Gnedin 2012). However, the number density of massive BHs formed is far more sensitive to other theoretical uncertainties, such as the actual mass

Parameters	h	Ω_0	$\Omega_{\rm b}$	σ_8	$n_{\rm s}$
adopted	0.7	0.3	0.047	0.83	0.96
WMAP9	0.700	0.282	0.0469	0.827	0.980
Planck	0.678	0.309	0.0483	0.829	0.961

Table 1. ΛCDM cosmological parameters used to compute the halo abundances in Fig. 2.
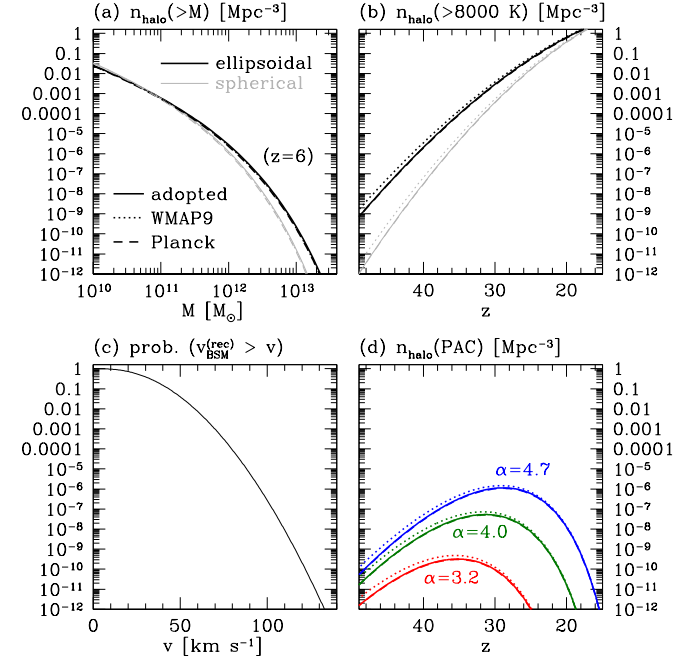
Figure 2. The rarity of relevant cosmological occurrences. Panel (a): the comoving number density of the most massive DM haloes at $z = 6$, assuming Sheth-Tormen ellipsoidal collapse (thick black lines) or Press-Schechter spherical collapse (thin grey lines). The different line styles correspond to different cosmological parameter sets (Table 1): solid lines for our parameter choices, dotted lines for *WMAP9* and dashed lines for *Planck*. Panel (b): the comoving number density of haloes with $T_{\rm vir} > 8000\,{\rm K}$ as a function of z. Line styles are as in panel (a). Panel (c): The likelihood that a given point in space has a recombination-value of the streaming velocity above a certain value v. Panel (d): the number density of haloes that have $T_{\rm vir} > 8000\,{\rm K}$ and also lie in a fast-streaming region where PopIII formation is prevented. The colors show different assumed values of the parameter α in the mass threshold estimate in equation 8: red, green and blue for $\alpha = 3.2$, 4.0 and 4.7, respectively. The line styles correspond to different cosmological parameters as in panels (a) and (b); only the Sheth-Tormen case is shown. (A color version of this figure is available online.)

scale on which PopIII formation occurs in the high-$v_{\rm BSM}$ regime (i.e. the effective value of the parameter α) and the efficacy of the collisional-dissociation scenario proposed by Inayoshi & Omukai (2012).

Fig. 2 allows one to place simple order-of-magnitude upper limits. From panel (a), the comoving number density of DM haloes massive enough to plausibly host the most massive SMBHs ($> 10^9\,{\rm M_\odot}$) at $z \approx 6$ is $\sim 10^{-6}$–$10^{-5}\,{\rm Mpc^{-3}}$, if we suppose the host halo must have a minimum mass of $\sim 10^{12}\,{\rm M_\odot}$. Comparing panel (c) of this figure with Fig. 1, we can estimate the likelihood of any such halo having grown in a region with sufficiently large streaming velocities to be PAC as $\sim 10^{-3}$–10^{-4}. Then, the comoving number density

of haloes that could host very massive SMBHs at $z = 6$ and that had streaming velocities high enough to have PAC progenitors may be as large as $\sim 10^{-9}$–$10^{-8}\,\mathrm{Mpc}^{-3}$, i.e. large enough to account for the most massive SMBHs (most luminous quasars) at $z \geqslant 6$ (Willott et al. 2010).

3.2 Merger-tree simulations

We use ellipsoidal-collapse DM merger trees (Zhang, Fakhouri & Ma 2008) convolved with the BSM velocity distribution to estimate the number density of massive BHs formed in fast-streaming PAC haloes. As stated above, BSMs suppress the abundance of high-mass haloes, but incorporating this effect in a merger tree code is a mathematically complex task. Therefore, for practical reasons, we treat the DM mass function and the BSM velocity fluctuations as being independent from each other. As a result, our simulations slightly overestimate the halo abundance, but this effect should be no more than a factor of ~ 2 at $z < 30$. The halo abundances also have numerical errors, typically less than a factor of 2 (see Fig. 4 below). As discussed above, these uncertainties are much smaller than those associated with PopIII formation and the efficacy of direct collapse in PAC gas clouds. We therefore do not believe that this simplification qualitatively affects our findings.

We simulate the merger histories of haloes with $z = 6$ masses $M_{\mathrm{halo}} \geqslant 10^8\,\mathrm{M}_\odot$. Our sample includes 60 individual haloes with $M_{\mathrm{halo}} > 10^{12.9}\,\mathrm{M}_\odot$ at $z = 6$, equivalent to a comoving volume of $\approx 50\,\mathrm{Gpc}^3$. The merger tree sampling method and algorithm are described in more detail in Tanaka & Haiman (2009; section 2.6) and Tanaka, Li & Haiman (2013), respectively; we refer the reader to these works for details. One key difference is that whereas in Tanaka, Li & Haiman (2013) a randomly generated streaming velocity value was assigned to each merger tree, here we convolve the halo sample with the velocity probability distribution function. More explicitly, the halo mass function is computed by counting the number of haloes in a given mass bin $M_{\mathrm{lo}} < M_{\mathrm{halo}} < M_{\mathrm{hi}}$ and dividing the sum by the effective comoving volume V of the simulation sample and by the logarithmic size of the bin: $\phi_{\mathrm{halo}}(M_{\mathrm{halo}}, z) = N(M_{\mathrm{lo}} < M_{\mathrm{halo}} < M_{\mathrm{hi}}, z)/V/\log_{10}(M_{\mathrm{hi}}/M_{\mathrm{lo}})$. Note that the simulated value of n_{halo} depends both on the fidelity of the merger tree algorithm in reproducing the theoretical mass function (which we have discussed in the first paragraph of this subsection), as well as on sample variance. As long as the sampling error is small (i.e. $N \gg 1$ for the given mass bin), given a sufficiently large volume the number density of PAC haloes is given by

$$\phi_{\mathrm{halo}}^{(\mathrm{PAC})}(M_{\mathrm{halo}}, z) = \sum p_{\mathrm{PAC}}(z)/V/\log_{10}(M_{\mathrm{hi}}/M_{\mathrm{lo}}), \quad (12)$$

where the sum is performed over the mass bin and p_{PAC} is the probability that a given halo resides in a region of space where the streaming velocity has a value such that the halo has had at least one PAC progenitor in its merger history.

In a given time step, a halo can become PAC if (i) its virial temperature exceeds 8000 K and (ii) the local streaming velocity is large enough (as defined by equation 8) so that it has not previously formed PopIII stars; and (iii) the velocity is small enough for gas infall and cooling to have

occurred. These conditions define a range or 'window' of streaming velocity values for which a given halo could have produced a massive BH; i.e., if the velocity is too low, the halo will already have formed stars before reaching $T_{\mathrm{vir}} = 8000\,\mathrm{K}$, and if it is too high, it will not have experienced gas infall and cooling (yet). When two atomic-cooling haloes merge, their velocity windows are also merged inclusively— e.g. if one progenitor could have formed a massive BH in the streaming velocity window $70\,\mathrm{km\,s}^{-1} < v_{\mathrm{BSM}}^{(\mathrm{rec})} < 80\,\mathrm{km\,s}^{-1}$ and the other has a window $85\,\mathrm{km\,s}^{-1} < v_{\mathrm{BSM}}^{(\mathrm{rec})} < 90\,\mathrm{km\,s}^{-1}$, then the merged halo will have at least one PAC progenitor if the local streaming velocity lies in either of these windows. The probability p_{PAC} that the local v_{BSM} value lies within the combined set of velocity windows is used to compute the abundance of PAC haloes (equation 12).

To keep this analysis as model-independent as possible, we make no *a priori* assumptions of the BH accretion rate, and only keep track of the number densities and mass functions of haloes that host at least one PAC progenitor. We also do not account for possible ejections of massive BHs via the gravitational recoil effect of BH mergers (Peres 1962; Bekenstein 1973; Favata, Hughes & Holz 2004; Haiman 2004; Yoo & Miralda-Escudé 2004; Baker et al. 2006; Schnittman & Buonanno 2007; Blecha & Loeb 2008; Guedes et al. 2008; Tanaka & Haiman 2009). The latter assumption is likely justified; the host DM haloes of interest have deeper potentials than those of PopIII stars and inhibit ejections. Further, even if a large fraction of BH pairings result in ejections, this should not affect the BH occupation fraction of massive haloes, as a typical $M > 10^{12}\,\mathrm{M}_\odot$ halo at $z = 6$ in a fast-streaming patch of space has $N_{\mathrm{prog}} \sim 10^2$–$10^3$ PAC progenitors that could have formed a massive BH. This can be seen from the top panel of Fig.3, where the number density of haloes with PAC progenitors decreases by a factor 10^2–10^3 for each α value considered.

An important related point is that massive $z \lesssim 10$ haloes that assembled in a fast-streaming region is likely to host a massive BH even if the fraction f_{DC} of PAC haloes—i.e. *potential* direct-collapse sites—that *actually* result in direct collapse is small. Again, the massive $z \lesssim 10$ haloes have consumed $N_{\mathrm{prog}} \gg 1$ PAC haloes via mergers. This means that as long as $f_{\mathrm{DC}} \gtrsim 1/N_{\mathrm{prog}}$, the number density of massive BHs at $z \lesssim 10$ is roughly independent of f_{DC}. That low BH occupation fractions can result in occupation fractions of unity at later times was shown by Menou, Haiman & Narayanan (2001) and Tanaka & Haiman (2009).

Fig. 3 shows the total number density of DM haloes that could host massive BHs formed in PAC haloes with large streaming velocities. The top panel shows the total comoving number density of host haloes as a function of redshift; note that at late times ($z < 20$), the number density goes down through hierarchical merging of haloes. The bottom panel shows the global seed formation rate. As with the previous figures, each curve assumes a different value of the parameter α that determines the threshold mass for PopIII formation: red dotted for $\alpha = 3.2$, green short-dashed for $\alpha = 4.0$ and blue long-dashed for $\alpha = 4.7$. The formation and merger rates of massive BHs made in the scenario considered here would be very low, with peak all-sky formation rates $\lesssim 10^{-3}\,\mathrm{yr}^{-1}$ per unit redshift, or no more than $\sim 10^{-2}\,\mathrm{yr}^{-1}$ integrated across all redshifts. Even if these
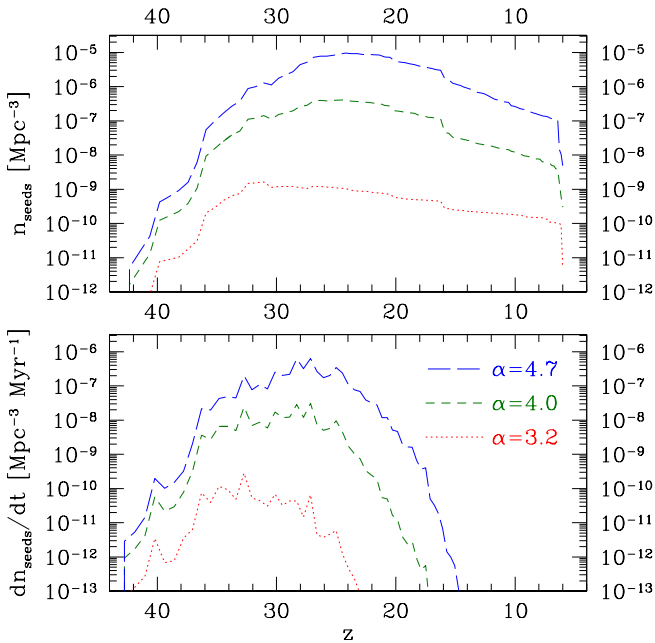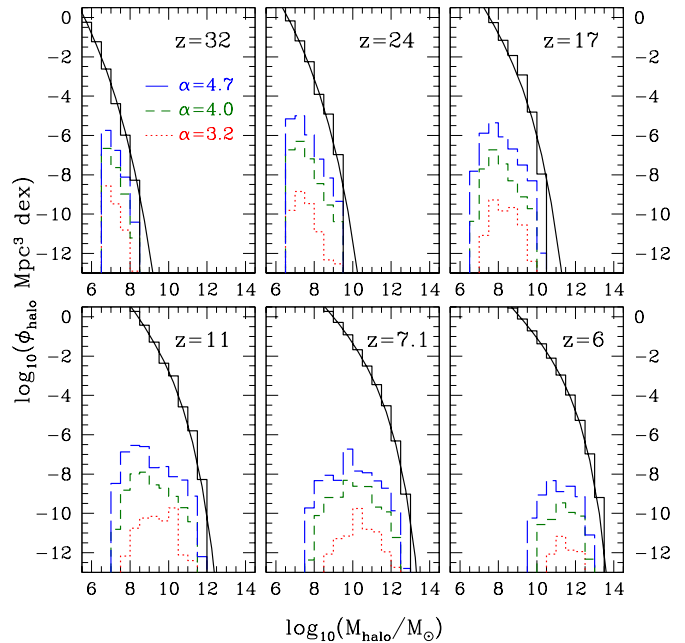
Figure 3. Top panel: estimated comoving number densities, as a function of z, of DM haloes containing at least one massive BH formed in PAC gas in rare, fast-streaming regions. Bottom panel: the rate at which haloes form massive BHs in this way. See text for caveats. (A color version of this figure is available online.)

Figure 4. The comoving number densities of PAC haloes formed in fast-streaming regions of the Universe, assuming halo mass thresholds for metal contamination in equation (8) for values of $\alpha = 3.2$ (red dotted lines), $\alpha = 4.0$ (greed short-dashed lines) and $\alpha = 4.7$ (blue long-dashed lines). The solid black curves and histograms show, respectively, the mass functions of DM haloes expected by the Sheth-Tormen formalism and those produced by the merger trees. (A color version of this figure is available online.)

$z > 20$ massive BHs formed in binary or multiple systems (e.g. Bromm & Loeb 2003), their mergers are unlikely to be observed by a gravitational-wave observatory such as *eLISA* (Amaro-Seoane et al. 2013) during its mission lifetime.

Fig. 4 shows the mass function of all DM haloes (solid black curves and histograms) and of those containing massive BHs formed in fast-streaming regions (colored curves), at redshifts $z = 32, 24, 17, 11, 7.1$ and 6. The *James Webb Space Telescope*[5] (*JWST*) is expected to be capable of detecting early quasars at $z \approx 11$; however, these massive BHs will have a sky density of $\lesssim 0.1\,\mathrm{dex}^{-1}\,\mathrm{deg}^{-2}$ per unit redshift (see, e.g., figure 4 in Tanaka, Li & Haiman 2013 for conversion of comoving n to sky density at $z = 11$) and thus are unlikely to be discovered by *JWST*, whose field of view will be $\sim 10^{-3}\,\mathrm{deg}^2$. The solid black curve shows the expected mass function in the Sheth-Tormen formalism, whereas the solid black histograms show the number densities produced by the merger trees. The differently colored histograms show the mass function of haloes containing at least one massive BH seed, with different colors and line styles showing the different assumed values for α as in all of the previous figures. As anticipated in §3.1, the number density of $z \approx 6$–7 haloes with $M > 10^{12}\,\mathrm{M}_\odot$ that contain massive BHs formed via large streaming velocities could be as large as $\gtrsim 10^{-9}\,\mathrm{Mpc}^{-3}$, i.e. large enough to account for the most massive quasar SMBHs observed at $z > 6$.

4   DISCUSSION AND CONCLUSIONS

We have proposed in this paper a path to massive BH formation via direct collapse of pristine, atomic-cooling (PAC) gas at $z > 20$. The mechanism has two sequential prerequisites, both of which have been discussed in the recent literature. First, large baryonic streaming velocities (Tseliakhovich & Hirata 2010) must be able to delay PopIII formation (Stacy, Bromm & Loeb 2011; Greif et al. 2011b; Fialkov et al. 2012; Naoz, Yoshida & Gnedin 2013) until the halo gravitational potential is deep enough to host atomic-cooling gas, i.e. until $T_{\mathrm{vir}} \gtrsim 8000\,\mathrm{K}$. Second, the gas that finally accumulates inside this halo must then undergo direct collapse, e.g. by forming a central cloud that is hot and dense enough ($T \gtrsim 10^4\,\mathrm{K}$, $n \gtrsim 10^3\,\mathrm{cm}^{-3}$) to collisionally dissociate H_2 and collapse via atomic cooling. In essence, the first condition facilitates the conditions for UV-free direct-collapse by providing a natural mechanism for forestalling PopIII formation and enrichment by metals and dust.

The feasibility of the first condition occurring in nature has been demonstrated, at least qualitatively, by recent three-dimensional simulations. Essentially, PopIII formation proceeds very rapidly via runaway H_2 and HD cooling when the central gas reaches certain density thresholds inside a halo with $T_{\mathrm{vir}} \gtrsim 1000\,\mathrm{K}$, and streaming velocities delay this transition. The key question, however, is just how large the streaming velocity must be to delay PopIII formation until the halo can host atomic-cooling gas, and whether such velocities occur frequently enough to explain the most massive of the $z > 6$ quasar SMBHs. If one extrapolates the

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[5] http://www.jwst.nasa.gov/

increase in the minimum PopIII-forming halo mass found by Stacy, Bromm & Loeb (2011) and Greif et al. (2011b) to large streaming velocities, as Fialkov et al. (2012) do, then the requisite velocity to stall PopIII formation until haloes become atomic-cooling is about two to three times the rms value ($\gtrsim 60\,\mathrm{km\,s^{-1}}$; Fig. 1). Naoz, Yoshida & Gnedin (2013) show that at such streaming velocities, gas fractions in $T_\mathrm{vir} \sim 8000\,\mathrm{K}$ haloes are indeed suppressed at $z \gtrsim 20$. These two sets of findings show that at least in principle, the first condition could be fulfilled in nature. However, there are significant uncertainties that have not been addressed by high-resolution simulations. As pointed out in §2, dynamical and compressional heating would be enhanced in the more massive, gas-poor haloes affected by large streaming velocities. Furthermore, the role of turbulence—which streaming velocities enhance—in promoting or suppressing PopIII formation has not been explored by simulations for the rare set of conditions discussed here.

A more general question is whether a PAC cloud can lead to direct collapse at all. While several studies have demonstrated the plausibility that direct collapse can occur in the absence of an external UV background, i.e. not via photodissociation but via collisional dissociation, detailed tests in numerical simulations are yet to come. Such conditions may lead to a 'supermassive' star that explodes instead of collapsing into a massive BH (see Johnson et al. 2013 and references therein). If UV-free direct-collapse occurs in nature at all, the streaming motions can facilitate it (i) by minimizing metal enrichment or even preventing it entirely, and (ii) through enhanced supersonic turbulence, promoting the creation of cold accretion filaments and increasing their kinetic energies. As argued above, the mechanism proposed here can result in a comoving number density $\sim 10^{-9}$–$\sim 10^{-8}\,\mathrm{Mpc^{-3}}$ of $z \approx 6$–7 haloes containing a massive BH *even if only a small fraction ($\lesssim 1$ per cent) of PAC haloes actually result in direct collapse.* The small fraction could be those that have low angular momentum or those that are clustered near strong UV sources (see refs. in §1).

Detailed hydrodynamical simulations are required to resolve both of these substantial theoretical uncertainties. High-resolution simulations of $T_\mathrm{vir} \lesssim 10^3\,\mathrm{K}$ DM haloes growing in large density peaks and amidst large streaming motions are needed to verify whether such conditions can forestall or minimize PopIII formation and metal enrichment until the halo potential is deep enough to support atomic-cooling gas and possibly shocking filaments. The simulations must then follow the gas in these haloes to confirm whether direct collapse can occur, as well as determine the degree to which collapse is sensitive to the metal content of the halo gas and to the magnitude of the streaming motions.

Of particular interest is the role of turbulence, which has been shown to be important in the formation of baryonic structures in both $T_\mathrm{vir} \sim 1000\,\mathrm{K}$ and $T_\mathrm{vir} \sim 10^4\,\mathrm{K}$ haloes (Greif et al. 2008, 2011a). Fernandez et al. (2013) found, in simulations of atomic-cooling haloes with pristine gas but without streaming velocities, that while gas in these haloes indeed do not cool efficiently, they also do not form the cool supersonic filaments envisioned by Inayoshi & Omukai (2012). It remains to be seen if such filaments can form with large streaming velocities, i.e. if the gas is more turbulent; similarly, the effects of supersonic turbulence on other proposed direct-collapse scenarios is uncertain.

If large baryonic streaming velocities can indeed stall PopIII formation until the earliest massive haloes reach $T_\mathrm{vir} \sim 8000\,\mathrm{K}$ (if $\alpha \gtrsim 4$, as Fialkov et al. 2012 find for Greif et al. 2011b), then these haloes will have gas that is PAC and exceptionally turbulent, making them promising potential cradles of direct collapse or exceptionally massive stars. These sites would preferentially emerge in a redshift range $20 \lesssim z \lesssim 40$ (Fig. 2 panel d, Fig. 3 bottom panel); at higher redshifts, haloes with $T_\mathrm{vir} \gtrsim 8000\,\mathrm{K}$ are too rare, whereas at lower redshifts streaming velocities are too low to delay PopIII formation. This is much earlier than the direct-collapse scenarios that rely on the emergence of UV sources at $z < 16$, and would produce rare $\sim 10^5\,\mathrm{M_\odot}$ BHs alongside the very first galaxies. The minimum time-averaged accretion rate required for such objects to grow into the observed $z > 6$ SMBHs is

$$f_\mathrm{Edd} \gtrsim \left[0.499 + 0.048 \ln \left(\frac{M_\mathrm{SMBH}}{3 \times 10^9\,\mathrm{M_\odot}} \frac{10^5\,\mathrm{M_\odot}}{M_\mathrm{seed}} \frac{1}{X_\mathrm{merge}} \right) \right]$$
$$\times \left(\frac{\eta}{0.07} \right) \left(\frac{t_\mathrm{avail}}{650\,\mathrm{Myr}} \right)^{-1}. \tag{13}$$

Comparing equation (13) above to equations (1) and (2), we see that these massive seed BHs offer as much of an advantage over direct-collapse seeds formed via large UV backgrounds as the latter do over PopIII seeds.

Several ways to observationally distinguish PopIII and direct-collapse models have been discussed in the literature (see Volonteri 2010, Haiman 2013). There is a degeneracy between most direct-collapse models and PopIII scenarios, in that both require (if the mean accretion rate does not far exceed the Eddington value) that $\sim 10^5\,\mathrm{M_\odot}$ BHs are in place before $z \approx 10$ (see, e.g., section 4.2.1 in Tanaka, Perna & Haiman 2012). Directly breaking this degeneracy—i.e. probing nuclear BHs at $z > 10$—will be extremely challenging, even with upcoming missions such as *JWST* and *Athena+*. It is also possible that SMBH progenitors are so rare (e.g. Tanaka & Haiman 2009) that they are unlikely to be observed in gravitational waves or through explosions of 'supermassive' stars. That being said, the scenario presented here can be corroborated if ever a massive ($> 10^4\,\mathrm{M_\odot}$) BH—or an associated signature, such as the explosion of a supermassive progenitor star or gravitational-wave signature—is discovered at $z > 16$ (where UV-aided direct collapse is unlikely).

Direct-collapse BHs are expected to have much larger masses with respect to their host halo mass than typical nuclear BHs (Bromm & Loeb 2003, Agarwal et al. 2013). They could be the progenitors of present-day SMBHs with unusually large masses compared to their galaxies, as in NGC 1277 (van den Bosch et al. 2012; Shields & Bonning 2013).

While a large baryonic streaming velocity cannot be the only pathway to SMBH formation (since SMBHs are present in virtually all galaxies, not just in rare patches of the Universe that had large BSMs), it can explain how a small number of SMBHs were able to grow to be exceptionally massive before $z \approx 6$–7.

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